

MECHANICAL PROPERTIES OF METALS AND FABRICATION

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IN NONREACTIVE ENVIRONMENTS

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By H. T. Simsic, Jr.

Ames Research Center, NASA

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ABSTRACT

Gas-metal interactions that occur in ambient environments and their effect upon mechanical properties of metals are briefly reviewed. Differences in mechanical properties measured in vacuum and in air or other gaseous environments are discussed in terms of type of test, basic processes of metal deformation and fracture involved, and possible reaction mechanisms. A concept of protective coatings to prevent gas-metal surface reactions and the specific effects of such coatings on fatigue properties of several metals are shown. The environmental effects are related to the problems of fabrication and end use.

INTRODUCTION

A major continuing problem in the fabrication of metal products - the forming, shaping, and assembly of parts into a structure - is the effect of environmental reactive gases in changing the properties of the metal. This problem has been reduced to some extent through the use of high-vacuum and nonreactive gas atmospheres. Some ingenious and unique fabrication techniques and facilities have been developed, but fabrication remains cumbersome, complex, and costly. In use, fabricated metal is protected from a reactive atmosphere by films or coatings.

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The discovery that many mechanical properties of metals are substantially different when measured in vacuum rather than in air led to the realization that surface reactions, primarily gas-metal, significantly affect the strength of metals. The discrepancies in mechanical properties measured in vacuum and those measured in air or "inert" atmospheres - sometimes referred to as "vacuum effects" - are the result of greatly decreased concentration of reactive gas species in vacuum and the accompanying elimination or minimization of gas-solid surface reactions. So-called "inert" atmospheres are generally not actually inert and nonreactive; the concentration of reactive species in one atmosphere of "inert" gas is orders of magnitude greater than in even a moderate vacuum. For example, 4 ppm of a reactive gas in 1 atmosphere of inert gas is equivalent to a partial pressure of about 10^{-5} torr of that reactive gas.

With this as a background, then, this paper reviews current knowledge of the mechanical behavior of metals in gaseous environments and in vacuum. Gas-metal interactions that occur in ambient environments and their effect upon mechanical properties will first be reviewed and discussed. Differences in mechanical properties measured in vacuum and in air or other gaseous environments (i.e., the environmental effect) will be discussed with reference to type of test, to basic processes of metal deformation and fracture involved, and to possible reaction mechanisms. One concept of protective coatings to prevent reactions between a gas and a metal surface, and the specific effects of such coatings on fatigue properties of several metals will be shown. Finally, environmental effects will, as appropriate, be related to the problems of fabrication and end use. The associated problems occurring during processing are, of necessity, beyond

the scope of this paper. The review is not intended to be all inclusive, but rather to provide examples of experimental results that effectively indicate the state of the art.

ENVIRONMENTAL EFFECTS ON MECHANICAL PROPERTIES

The primary environmental reaction, other than thermal, that can change mechanical properties of metals, is that of reactive gases in the ambient atmosphere, which can cause gross changes in metallurgical structure. These changes include the formation of surface oxide scale, of carbide or nitride surfaces, or oxidation along grain boundaries. Changes in mechanical properties that cause less obvious alterations in microstructure are the strengthening effects that can occur from fine-particle precipitation of oxides, nitrides, hydrides, and carbides in the interior of the metal. These effects usually result from reactions with impurities introduced by the environment in small quantities. Similar contamination by even smaller amounts of interstitial elements throughout the matrix of some metals can result in a pronounced strengthening effect accompanied by only very slight change in crystallographic structure.

Surface films also can significantly affect the mechanical properties of metals. Roscoe¹ demonstrated in 1934 that solid, thin films of oxide on cadmium crystals had a pronounced effect on their mechanical properties. Since that time, numerous investigations have shown convincingly that the mechanical properties of metals are environment-sensitive in that they are affected by environment-induced changes in the metal surface. Atomically thin, adsorbed surface films, quantitatively too minute for chemical

composition analysis, can cause modifications in mechanical properties that can be detected in an inert-gas or vacuum environment.

Until 1960, the number of investigations into the effects of vacuum on the mechanical properties of metals² was small in comparison with investigations into the corresponding effects on aqueous and gaseous environments.³ Investigations of vacuum effects on materials have accelerated, however, in response to the increasing interest in aerospace materials applications. Since vacuum and inert-gas environments are extensively used in the fabrication of many metals, the effects of these environments on the mechanical properties of the metals must be determined.

Investigation of material properties that may be affected by formation of atomic or molecular surface films requires the preparation (or generation) of a contamination-free surface, and the capability to maintain it throughout the experiment. The time required to form a monomolecular film on an initially clean surface⁴ is a function of the pressure of the ambient atmosphere. Assuming that every molecule striking a surface is adsorbed, or sticks, this time can be calculated on the basis of the kinetic theory of gases. As a function of pressure, figure 1 shows the time required for the formation of a surface monolayer in air. If the time required for a test is only a few seconds, then a vacuum of about 10^{-6} torr is sufficient to prevent complete contamination of the surface. Because of the times involved and operating pressures attainable in fabrication processes, prevention of surface film contamination cannot be expected. In testing, however, meaningful results can be obtained in time periods less than those required for complete surface contamination and at test pressures attained without great difficulty. In tensile, fatigue, and

creep tests, the clean surfaces required for investigation of surface effects are generated during the test itself. In adhesion tests, surface-cleaning techniques are sometimes used, or fresh surfaces are created by controlled fracturing of the specimen in vacuum.

The magnitude of the effect of a gaseous environment on mechanical properties of metals clearly depends on generation of fresh surfaces by the flow and fracture processes involved in each type of test. Since the flow and fracture characteristics of materials in turn are affected by grain size and intergranular surface area, these factors also must be considered in any study of changes in bulk properties induced by external surface effects.

Tensile Properties

Higher tensile strengths or lower ductility of metal single crystals tested in gaseous environments than those tested in vacuum have been reported by almost all of the investigators in this field, as shown by the results mentioned below of studies on various metals made by different investigators. For polycrystalline material, when a difference has been observed between tests made in the two types of environments, increased ductility was found for vacuum tests.

The effect of environment on room temperature tensile strength of single-crystal aluminum has been demonstrated by Kramer and Podlaseck.⁵ The strengthening effect of an atmospheric oxide film on this metal is shown in figure 2 where the strength of the two specimens tested in air is significantly greater than their strengths in vacuum; note that this greater strength of the two crystals in air carried over to a comparable difference at 10^{-6} torr. Nelson and Williams⁶ found that single crystals of magnesium

demonstrate a pronounced vacuum effect similar to that for aluminum. They observed that the magnitude of the effect also depended on strain rate and vacuum level, as shown in figure 3. This figure shows, as a function of pressure, the percent change in strain $\Delta\epsilon$ at the end of the first linear stage from that observed at 1 atmosphere of air for strain rates of 6.7, 0.67, and 0.067 min^{-1} . For each strain rate, there appeared to be a pressure range above and below which changes in vacuum level had little effect; for a strain rate of 0.67 min^{-1} , for example, this range was approximately 5×10^{-7} to 1×10^{-6} .

In tests on polycrystalline magnesium sheet specimens with gage cross section $1/2" \times 1/4"$, no vacuum effect was observed on fine-grained (0.01 mm) specimens; but specimens of larger grain size (0.20 mm) showed improved ductility over similar specimens tested in air as indicated by the stress-strain curves of figure 4. In the usual tensile test of ductile metals, reduction of the gage area of the specimen, indicative of plastic flow, takes place before final rupture. Since the metal flow occurs throughout the necked-down region, the test environment would not be expected to have an appreciable effect on the tensile properties unless the ratio of surface area to intergranular area were high, as with single crystals. The observed effects of vacuum on metal single crystals has been qualitatively related^{5,7} to the formation in a gaseous environment of films on the new surface created by deformation. The surface film, it is postulated, acts as a barrier to the movement of dislocations out of the metal. The resulting pile-up of dislocations at or near the surface impedes their mobility during the deformation process, which, in turn, produces an increased work hardening rate and higher tensile strengths. In vacuum tests in which

fresh metal surface is created more rapidly than a surface film can be formed by gaseous impurities in the environment, there is no barrier on the film-free part of the surface to the unimpeded egress of dislocations; consequently, there is decreased pile-up of dislocations and lower strength. The dependence of a vacuum effect on strain rate, noted for magnesium single crystals, similarly can be explained in terms of the relation between strain rate, which determines rate of creation of new surface, and pressure level, which determines rate of film formation on the new surface.

For polycrystalline material specimens of normal size and grain size in which the intergranular surface greatly exceeds the external surface area, the immobilizing effect of the intergranular surfaces on the motion of dislocations can completely mask the effect of film formation on new surface area created by the tensile test. As the ratio of surface area to intergranular area increases with increasing grain size and decreasing specimen size (cross section), the effect of a film on newly created surface becomes proportionately greater, reaching a maximum regardless of specimen size when the number of grains is reduced to a single crystal. For very small specimens - for example, fine wire, whose average grain diameter may approach the specimen diameter - the ratio of surface area to intergranular area is high, and the test environment affects tensile strength.

Creeep Properties

Many investigations have been made of the effect of environment on creeep properties of various metals. The results, however, are difficult to correlate because of the complexity of deformation mechanisms and

kinetics involved. At high temperatures, for example, plastic flow within grains and grain boundary sliding accounts for unknown portions of the deformation during creep.

Strengthening by oxidation from gaseous environment at high temperatures has been reported by McCoy and Douglas⁸ among others, on Type 304 stainless steel, by Cass and Achter⁹ on nickel, and by Shahinian and Achter¹⁰ on the nickel-chrome alloys. Data reported by Shahinian and Achter for creep of a nickel-chromium alloy at 1100°F in air and vacuum, shown in figure 5, are typical of the oxide-strengthening effect of air environments on metals. They also found, however, that the effect of air on the rupture time of nickel undergoes a reversal,¹¹ as shown in figure 6. The metal was stronger in vacuum at high stresses (shorter exposure times) but stronger in air at low stresses. Nelson and Williams⁶ also observed a diverse vacuum effect on the creep resistance of magnesium compared with those determined in an air-argon environment at 1 atmosphere. The results are shown in figure 7 as steady-state creep rate versus reciprocal temperature. Depending on temperature, magnesium may exhibit at a given stress level either large increases or decreases in its creep resistance in vacuum compared with an air-argon environment. Nelson and Williams have suggested that either vacuum may activate a deformation mechanism not previously observed in gaseous environments, or the assumptions on which the steady-state creep equation is based are not valid for creep in vacuum.

For long-time tests at elevated temperatures in which strengths are higher in air than in vacuum, the evidence of Achter¹² and his co-workers showed that strengthening occurs through internal oxidation with oxide particle precipitation. In comparable short-time tests, he found that

exposure was insufficient for this process to be effective. However, in these short-time tests and in the absence of other factors, the strengthening effect of a surface film should result in higher strengths in air than in vacuum. If the absence of this film-strengthening effect is due to the propagation of cracks from the surface inward as in fatigue testing, as appears to be the case for all tests that showed lower creep strength in air than in vacuum, the controlling mechanism must consist in the causes of higher fatigue properties in vacuum than in air, discussed in the following section.

Fatigue Properties

Following the work of Gough and Sopwith¹³ on copper and brass in 1932, a number of investigators have demonstrated that several metals have better fatigue properties in vacuum than in air. Other investigations have shown that the fatigue properties of metals are affected by gaseous atmospheres, or by their absence in high vacuum. Water vapor has been reported to have a deleterious effect on the fatigue properties of metals. Mantel et al.¹⁴ found that 52100 steel had longer fatigue life in dry argon than in wet argon. Water vapor was found by Broom and Nicholson¹⁵ to be the only constituent of normal air that decreased the fatigue life of aluminum alloys, and Bennett¹⁶ has reported that a reduction in relative humidity from 90 percent to 3 percent resulted in a four- to fivefold increase in the fatigue life of aluminum and magnesium alloys. Gough and Sopwith¹⁷ found that the simultaneous presence of oxygen and water vapor was necessary to reduce the fatigue limit of copper. The same combination of gases has been found by Bradshaw and Wheeler¹⁸ and Nelson and Williams⁶ to critically affect the fatigue properties of aluminum and magnesium alloys, respectively.

Improved fatigue properties of metals tested in vacuum compared with those tested in air have been reported by several investigators in addition to Gough and Sopwith:¹³ Wadsworth¹⁸ for steel, copper, aluminum, and aluminum alloys; Wadsworth and Hutchings²⁰ for copper and aluminum; Snowden²¹ for aluminum and lead; Pan,²² Kramer and Podlaseck,⁵ Shen et al.,²³ and Hordien²⁴ for high-purity aluminum; Nelson and Williams⁶ and Summison²⁵ for magnesium and magnesium alloys. Figure 8 shows the S-N curves (maximum outer fiber stress versus cycles to failure) for unalloyed magnesium in reverse-bend flexure tests in air and in vacuum. The marked improvement of fatigue properties in vacuum is evident. Investigations have shown that the effect of improved fatigue properties in vacuum over those in air observed at room temperature can be reversed at high temperatures. Danek et al.²⁶ found that for nickel in reverse bending at 1500°F as shown in figure 9, there is a reversal in the atmospheric effect for 0.060-inch specimens but not for thicker 0.118-inch specimens; the 0.060-inch specimens at the higher strains or stress have longer fatigue life in vacuum than in air, but as the strain is decreased, there is a crossover point below which fatigue life is longer in air.

Investigations into the effect of changes in the ambient gas pressure on fatigue life revealed continuous variation between the two in some instances and a stepped variation in others. Figure 10 shows the continuous variation in the fatigue life of copper, aluminum, and aluminum alloy as a function of pressure that was found by Wadsworth¹⁸ and Wadsworth and Hutchings.²⁰ Figure 11 is an example of the stepped variation reported for magnesium by Summison²⁵ and shows a transition pressure range of 1 to 10^{-1} torr, above which the decrease in fatigue properties occurred for the conditions of that particular test.

The continuous variation reported by Madsworth and Hutchings^{18,19} for copper, aluminum, and aluminum alloy also was found for aluminum by Kruger and Podlaszek,² and by Snowden.²¹ The stepped variation reported by Summion²² for magnesium has also been found for lead by Snowden,²¹ for aluminum by Han,²³ Shen et al.,²⁴ and Hordern.²⁵ Bradshaw and Wheeler¹⁶ found the stepped variation for the effect of water vapor on aluminum alloy.

Most investigations of the difference in fatigue life of metals in gaseous and vacuum environments have been made on polycrystalline materials. While the concept of increased tensile strengthening by the surface film effect is not considered applicable to specimens of normal size and grain size, the basic concept is applicable on a microscopy or sub-grain size scale. The absence of a surface film increases the ease with which dislocations move out of the metal during plastic flow which results in readier deformation of the metal near the tip of the cracks, and, thus, a greater blunting of the crack tip. Consequently, it should be more difficult for the crack to propagate and the longer fatigue life in vacuum could result. Furthermore, if this is the mechanism of the effect of vacuum on fatigue, the effect of pressure on fatigue life should be similar to the effect of pressure on single-crystal tensile deformation. This similarity has been noted, and in both cases, the change from properties characteristic of deformation in air to those for vacuum occurred in a similar manner over a range of pressure. In addition, fracture surfaces indicate that specimens tested in vacuum have fractured in a more ductile manner than those tested in air.

The above concept does not explain the reversal of the vacuum effect during high-temperature fatigue tests - that is, reversal from lower to

higher fatigue strength in air than in vacuum shown in figure 9 for the 0.060-inch nickel specimens. A possible explanation is bulk strengthening by internal oxidation and fine-particle precipitation resulting from continued exposure at high temperatures to the oxidizing effects of the atmosphere. The thicker specimen would require longer exposure for its greater volume to be strengthened by the oxide precipitation reaction. A possible explanation of the occurrence of both the continuous and the stepped variation of fatigue life with pressure is that the continuous variation represents an extended transition range for the test conditions of the specific investigation.

Adhesion or Cold Welding

Adhesion tests determine the bond or weld strength between two surfaces brought in contact. An initially clean surface is necessary for reliably determining the effect of surface contamination in reducing bond strength. Cleaning techniques sometimes used include ion bombardment, heating to absorb or desorb contaminants or evaporate surface layers, and brushing or other means of mechanically removing surface layers; this technique must, of course, be used to determine welding or bonding between dissimilar metals. A more widely used technique for creating fresh surfaces is the fracturing of notched specimens under high vacuum test conditions.

A number of investigators²⁷⁻³⁰ have found that adhesion for a metal is determined by its bulk and surface properties, and interaction with its gaseous environment. The amount of adhesion is related directly to surface contamination by chemisorbed gases, which can be expressed as integrated exposure to contaminating environment up to a leveling-off or saturation point representing complete contamination of the test surfaces. Results

of a recent study by Gilbreath³¹ showed that surfaces could be effectively contaminated only by chemisorbed gases; physically adsorbed inert gases had little effect, at least at pressures less than 1 atmosphere. Figure 12 shows the effect of gaseous contamination on adhesion bond strength. The normalized adhesion coefficient (normalized to eliminate the effects of work hardening from repeated compression on adhesion) is plotted as a function of integrated exposure in torr sec (the product of pressure in torr and exposure in sec). The adhesion coefficient is a measure of bond strength with a coefficient of unity representing complete rewelding. As shown, complete contamination is reached in an environment of air or O_2 with an exposure of about 10^{-3} torr sec, and for C_2H_4 at about 10^{-2} torr sec. The differences between the effects of O_2 and C_2H_4 , both chemisorbed gases, are correlated with the differences in heat of adsorption of the two gases and the effect of these differences on the rate of surface contamination. The decreases in adhesion noted in environments of H_2 , N_2 , or Ar are attributed to small amounts of active gas impurities.

Effect of Protective Coatings on Fatigue Properties

There is strong evidence that the improved fatigue properties of metals tested in vacuum are due to the nonoccurrence of a reaction between the reactive gases normally present in the atmosphere and the new metal surface created by a fatigue crack. It is of interest, therefore, to determine if a protective coating or film applied to a metal surface, by blocking contact of the reactive gases with the new metal surface of the fatigue crack, could prevent the gas-surface reaction in air and, thereby, result in fatigue properties similar to those found in a vacuum environment. If so, coatings

might be used to isolate metal parts that are subject to critical fatigue stresses and fatigue behavior could be improved with subsequent increases in allowable fatigue design criteria. Also, coatings could be used for protection of those components or parts of space vehicles that have critical fatigue properties and could benefit by enhanced fatigue behavior during the launch period when the vehicle is temporarily subjected to severe vibrations. The coating would have to be sufficiently ductile to withstand without fracture the strains imposed by the cyclic stresses encountered.

Results of flexure fatigue tests of polymer-coated specimens are shown in figure 13, which compares S-N fatigue data for these coated specimens with the previously mentioned uncoated specimens tested in air and in vacuum. The enhanced fatigue properties of the coated samples are equivalent to those obtained in vacuum tests; the slightly greater scatter is thought to result from the added test variables of coating integrity and durability. Tests also have been made on magnesium and magnesium-thorium specimens with aerosol spray coating, and on 1100 aluminum and 7075 T6 aluminum specimens with protective polymer coatings. All coated specimens showed fatigue properties significantly greater than uncoated specimens. A summary of fatigue data comparing air, vacuum, and coated tests is given in figure 14, which shows the fatigue limit at 10^8 cycles for magnesium, magnesium-lithium, magnesium-thorium, 1100 aluminum, and 7075 T6 aluminum for the three test conditions. Coating increased the strength of magnesium 55 percent, a magnesium-thorium alloy and a magnesium-lithium alloy 20 percent, aluminum 15 percent, and 7075 aluminum alloy 40 percent for 10^8 reverse-bend cycles in air at normal pressures

and temperatures. The increase of air-tested fatigue properties to values close to vacuum-tested specimens is attributed to the effectiveness of the coatings in apparently excluding the ambient atmosphere from contact with the new surface of the fatigued specimens.

FABRICATION OF METALS IN USEFUL NONREACTIVE ENVIRONMENTS

In the absence of an ideal, completely nonreactive environment for fabricating metals, actual practice has been to select, on the basis of what is known about gas-metal reactions, the environment that most closely meets the requirements of the metal system being fabricated. The problems of contending with extreme oxidation of refractory metals in air at high temperatures are well known. These reactions are typical of gas-metal interactions that cause gross changes in metallurgical structure. With metals such as molybdenum and tungsten for which the reaction product of this kind of interaction is a nonadherent layer or scale, the harmful effect of structure change by oxygen penetration can become catastrophic at the high temperatures required for hot working processes and for some applications. Yet these metals are taken through all the necessary metal-working processes in air or production vacuum furnaces by suitable limitations of exposure times and temperatures, accompanied by appropriate cleaning processes, such as descaling, pickling, and grinding, to minimize incorporation of contaminated material into the metal matrix.

The extent of contaminating reaction can be lessened by using a protective inert atmosphere in which the reactive gas content has been reduced to low concentrations, or by evacuating the atmosphere from the chamber containing the metal, leaving only residual traces of the contaminating

gases. The container surrounding the metal can also be an evacuated and sealed encapsulating jacket, which accompanies the reactive metal or metal compact through subsequent fabricating processes for which a non-reactive atmosphere is essential. A variation of this technique is roll bonding, in which the atmosphere is excluded from the substrate metal by the cladding material. Protective coatings or films also are used extensively to provide, in effect, a nonreactive environment. In fabrication processes, lubricating solutions are also used to provide a nonreactive interface between contacting surfaces of the fabricating equipment and the metal being processed.

The InFab Facility at Specialty Steel Division of Universal Cycles Steel Corporation is a unique example of a usable nonreactive metal fabricating environment. It was designed and constructed to process refractory metals at true-hot-working temperatures up to 4000°F with optimization of alloy properties and minimum contamination or property degradation. It has been used successfully since its completion in 1960 in a number of Navy and Air Force programs to achieve true hot forging of molybdenum alloys, as well as the forging and/or rolling of high-strength columbium and tantalum alloys.³² Sound contamination-free fusion welds in a number of columbium, molybdenum, and tantalum alloys have been produced, and the feasibility of welding large, complex structural components of these metals has been demonstrated.³³ To achieve these accomplishments, the total impurity level of the argon environment was maintained at approximately 10 ppm. With this facility, it was found that, with an impurity content of 4 ppm oxygen and 10 ppm water, the degree of contamination introduced into columbium on exposures up to 1 hour at temperatures up to

4000°C was approximately equivalent to that caused by a vacuum of 10^{-3} torr.³⁴ This contamination effect of the argon atmosphere is less, by two orders of magnitude, than that calculated earlier, where 4 ppm contamination in an inert gas is comparable in terms of total reactive species present to a pressure of about 10^{-3} torr. Reasons for this discrepancy are not entirely clear to the author.

As has been well established by experimental investigations and operating experience, refractory metals and their alloys are subject to either contamination or purification, depending on exposure conditions of temperature and environment. The increase in tensile strength of columbium due to small increases in oxygen content illustrates the marked effect on mechanical properties of small amounts of interstitial elements through solid solution strengthening. Figure 15 shows the ultimate tensile strength of columbium versus temperature for three oxygen-concentration levels: 0.001 percent, 0.02 percent, and 0.43 percent.³⁵ An increase in oxygen content from 10 to 200 ppm at 500°C increased the tensile strength by approximately 50 percent, from 28,000 to 42,000 psi. If a fabrication process for such a highly reactive metal required holding at temperatures that could result in minor pick-up of interstitial elements, the use of a vacuum environment may be indicated since it allows a lower concentration of residual contaminants than does an inert atmosphere. If reduction of interstitial contamination of tungsten or molybdenum alloys during heat treatment is required, then a vacuum environment is again necessary. On the other hand, if metals of high vapor pressure such as cadmium, magnesium, zinc, or their alloys must be held for any length of time at temperatures at which evaporation would take place, the use of inert-gas atmospheres must be considered. In alloys,

high vapor pressure elements may evaporate, causing depletion of these elements at the surface. Concentration gradients in the metal are thus created and these elements will migrate by diffusion to the surface for subsequent evaporation, resulting in formation of voids, and changes in composition and microstructure in the metal.

Bourgette³⁸ determined the evaporation characteristics of Haynes alloy 25 (composed of 49 percent cobalt, 20 percent chromium, 16 percent tungsten, 11 percent nickel, and minor amounts of iron, manganese, silicon, and carbon) over the temperature range of 870° to 1100°C, in high vacuum (5×10^{-7} torr and lower). Evaporation rates were found to be highly temperature-sensitive, as expected, and at constant temperature decreased with increase in exposure period, as shown by figure 16. Changes in the composition of the vapor deposits, determined by analyses of samples taken at successive time intervals, showed that the higher vapor pressure alloying elements, manganese, chromium, iron, and nickel, were preferentially evaporated. Depletion of these elements at the surface was evidenced by the concentration gradients of these elements between the interior and the surface, as shown by electron probe microanalysis of the specimens. The continued loss of these elements was dependent on the diffusion rate in the cobalt-tungsten matrix which accounts for the noted decrease in evaporation rate with temperature and time. This material transport by diffusion, accompanied by coalescence of voids beneath the surface, resulted in a honeycomb structure near the surface with uncoalesced microvoids throughout the specimens.

Finally, with reference to the increased ductility which metals have in vacuum compared to air, it would be desirable in the deformation

processing of metals to take advantage of this property, even though the excessively short time for surface contamination limits its consideration for application in the atmosphere of earth. At pressures of 10^{-9} torr, somewhat more than one-half hour is required to form a surface monolayer. Vacuum chambers with considerable working space can achieve pressures of this order without great difficulty. Within these presently attainable parameters of time and pressure, the potentially beneficial effect of vacuum on metal deformation appears worthy of investigation.

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FIGURE LEGEND

- Figure 1.- Variation of surface contamination time with pressure.
- Figure 2.- Strain of aluminum single crystals in air and vacuum.⁵
- Figure 3.- The effect of pressure and strain rate on strain of magnesium single crystals.⁶
- Figure 4.- The effect of vacuum on the tensile properties of polycrystalline magnesium.⁶
- Figure 5.- Creep of a nickel-chromium alloy at 1100°F and 60,000 psi in air and vacuum.¹⁰
- Figure 6.- Creep-rupture of nickel at 1200°F and 1500°F in air and vacuum.¹¹
- Figure 7.- Creep properties of polycrystalline magnesium in air and vacuum.⁶
- Figure 8.- Flexure fatigue of magnesium in air and in vacuum.²⁵
- Figure 9.- Fatigue of nickel at 1500°F in air and vacuum.³¹
- Figure 10.- Variation of fatigue life with pressure for pure copper and aluminum and an aluminum alloy.^{18,20}
- Figure 11.- Effect of pressure on the fatigue behavior of magnesium.²⁵
- Figure 12.- Effect of exposure to various gas environments on the adhesion coefficient of high purity aluminum.³²
- Figure 13.- Fatigue properties of coated and uncoated magnesium specimens.²⁵
- Figure 14.- Effect of vacuum and protective coatings on fatigue properties of various metals.
- Figure 15.- Effect of oxygen content on the strength of columbium.³³
- Figure 16.- Changes in the evaporation rate of Haynes alloy with exposure time.³⁵

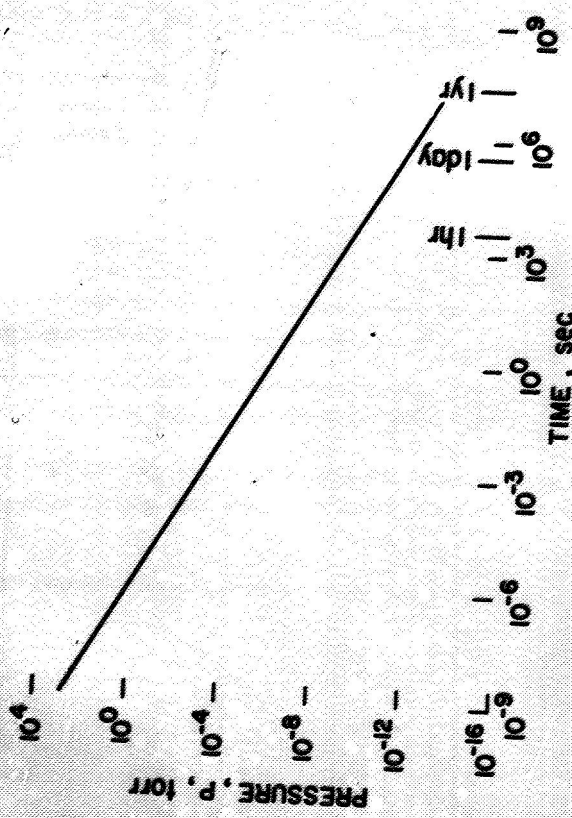


Figure 1.

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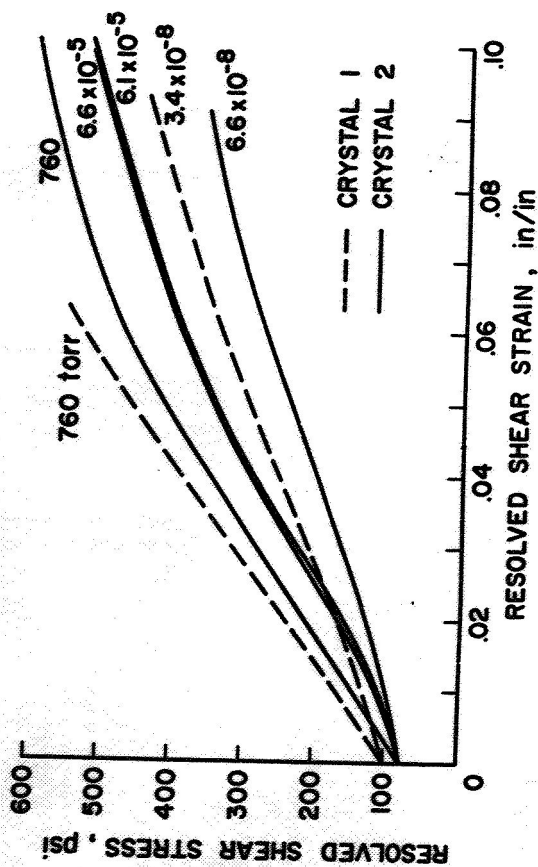


Figure 2.

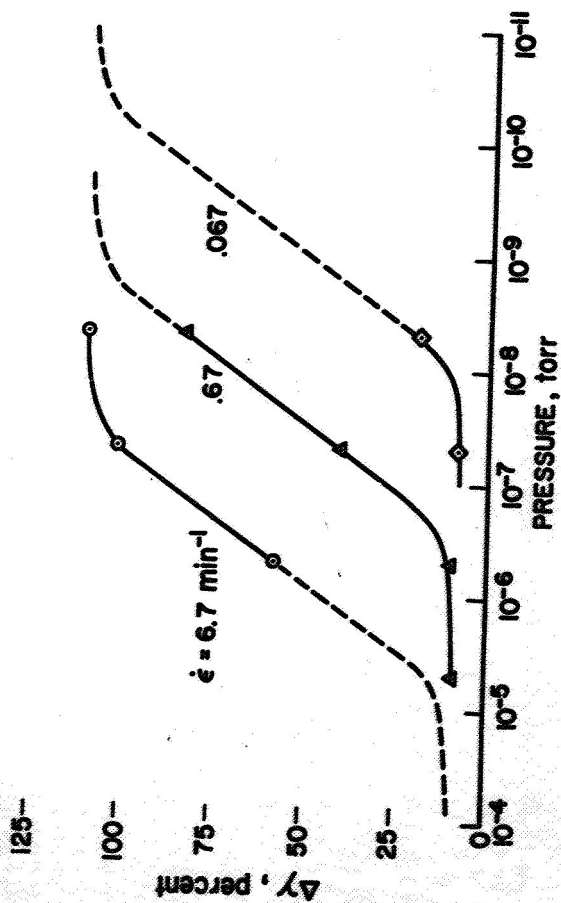


Figure 3.

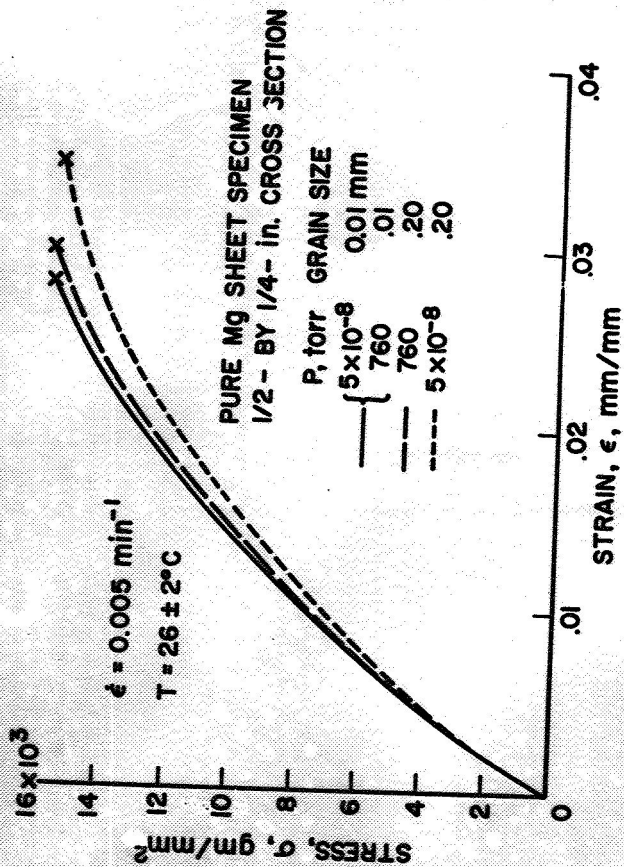


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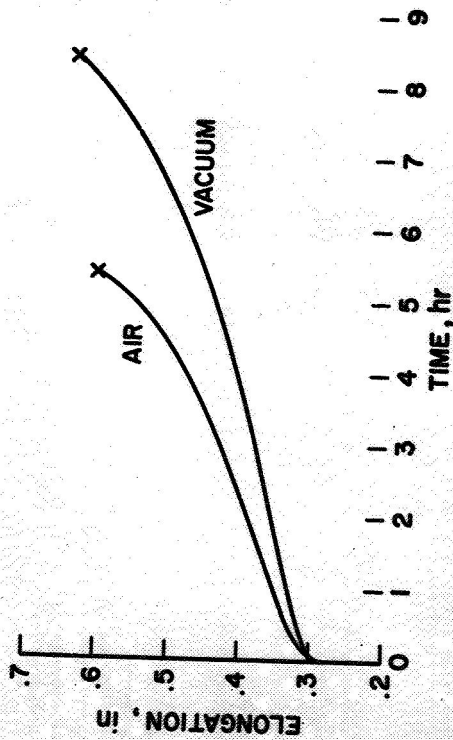


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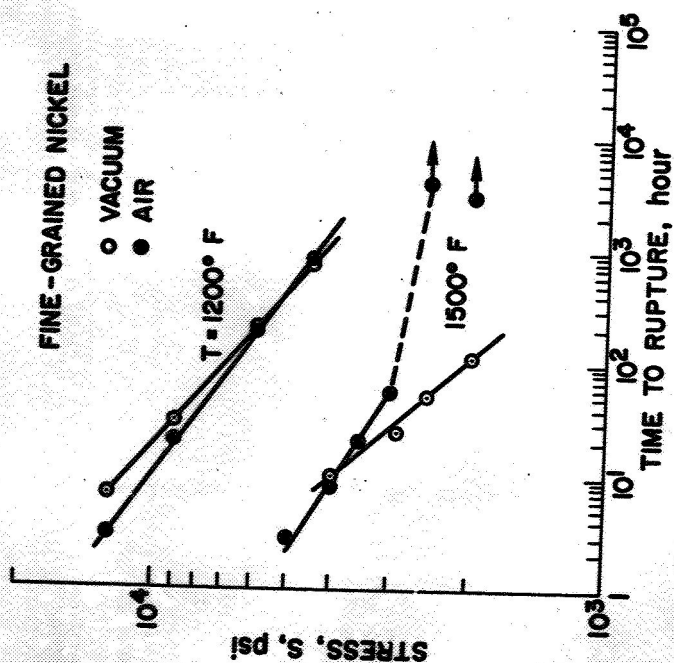


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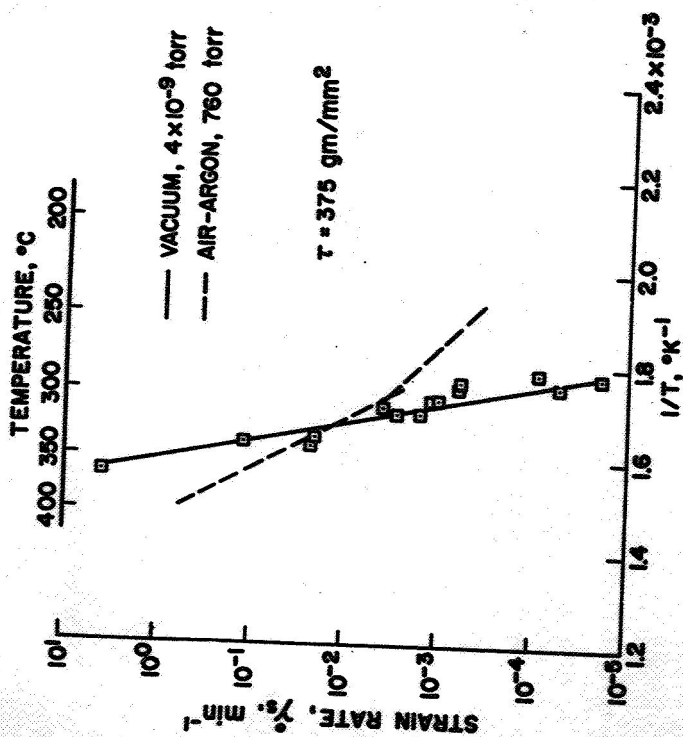


Figure 7.

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 "AND STRAIN RATE, TEMPERATURE AND RATE OF DEFORMATION"

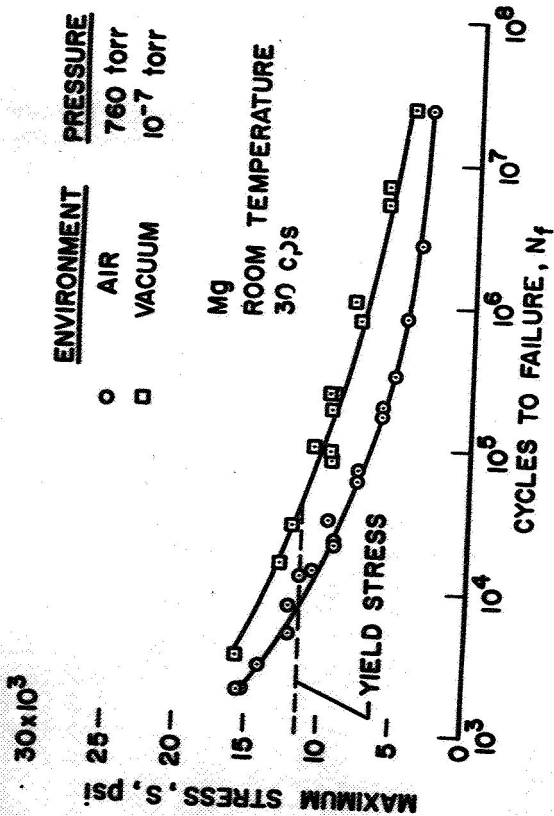


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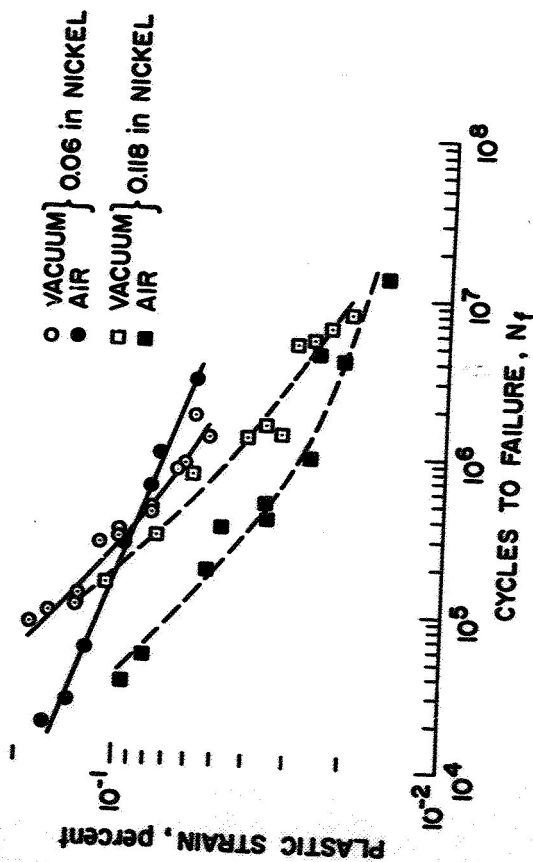


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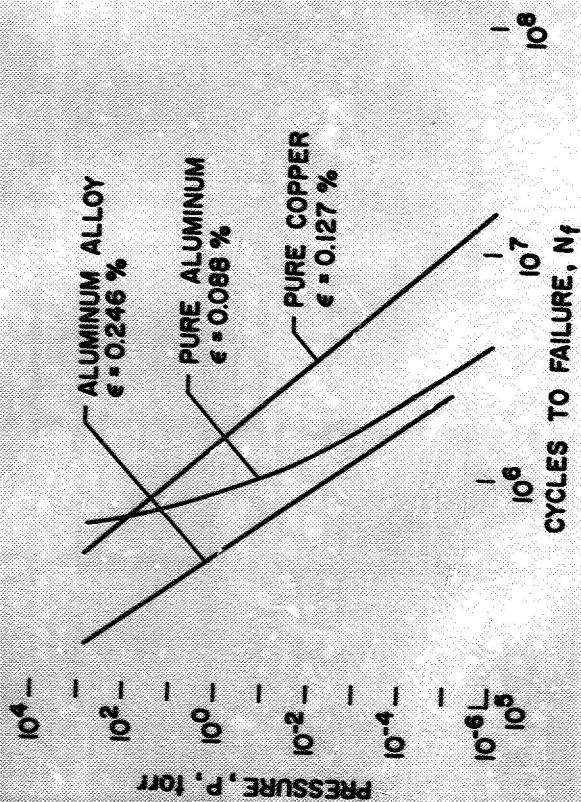


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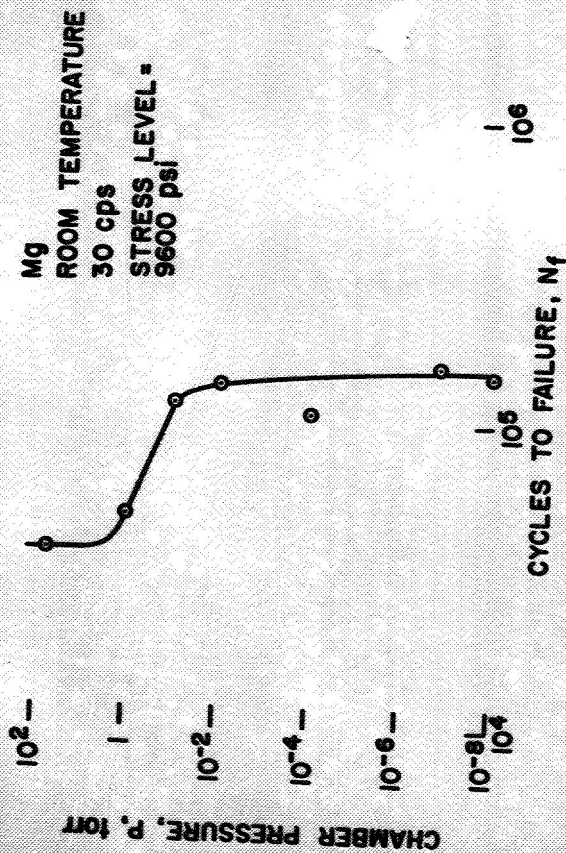


Figure 11.

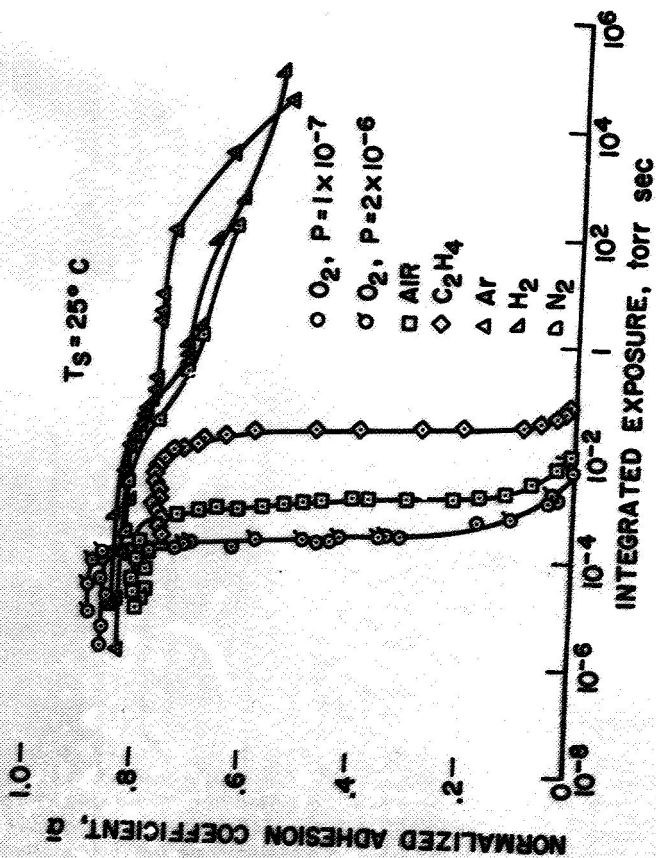


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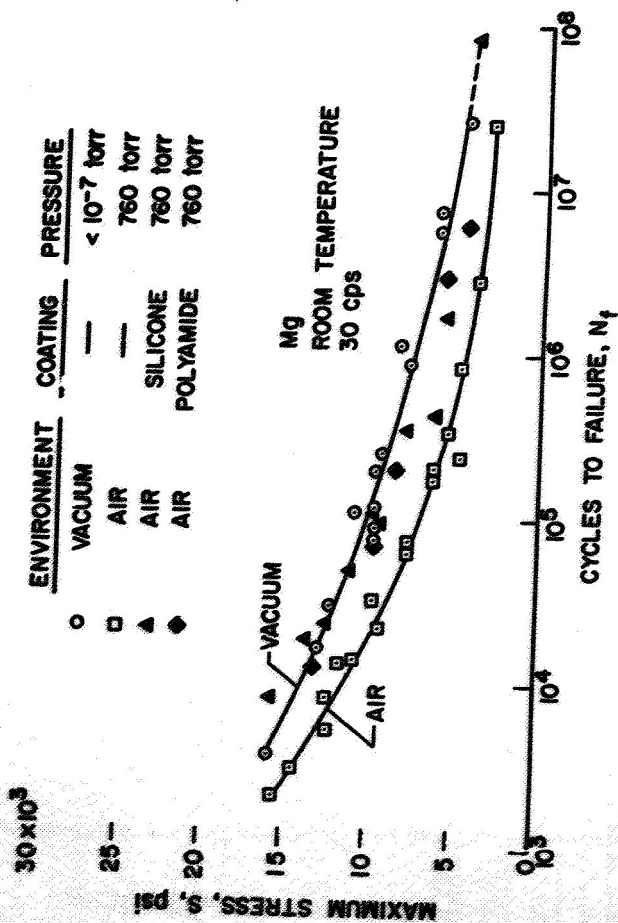


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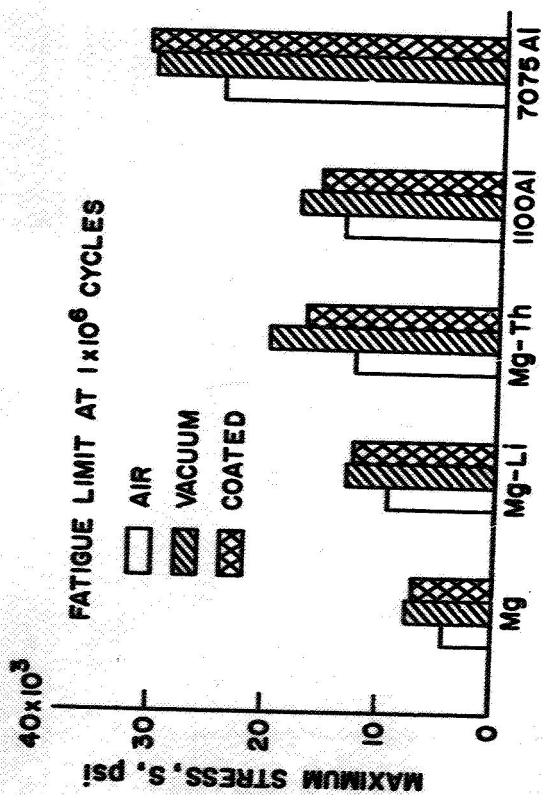


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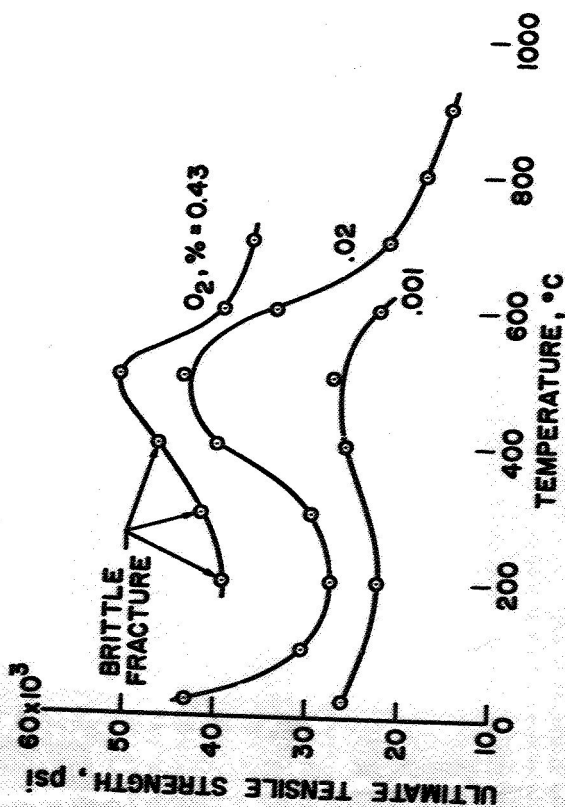


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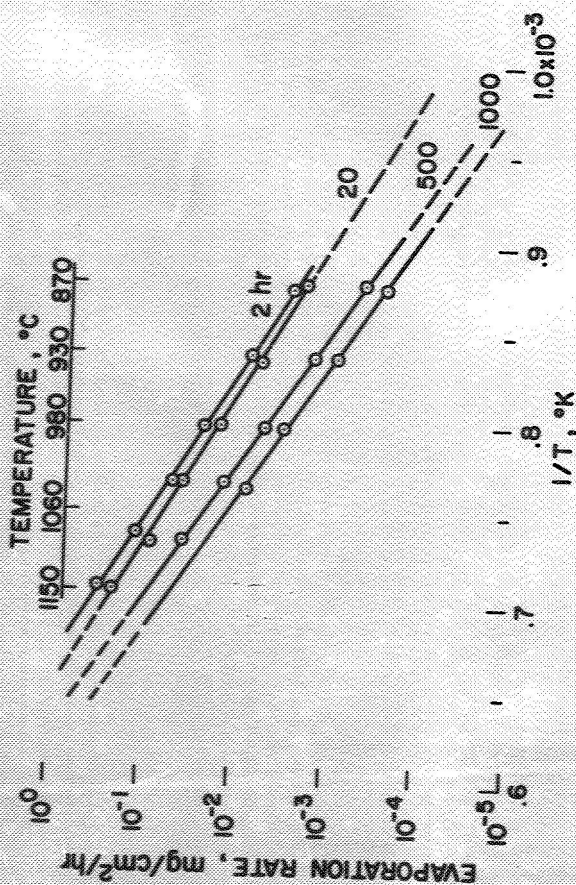


Figure 16.

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